Charging and bunkering infrastructure for zero emission high-speed vessels

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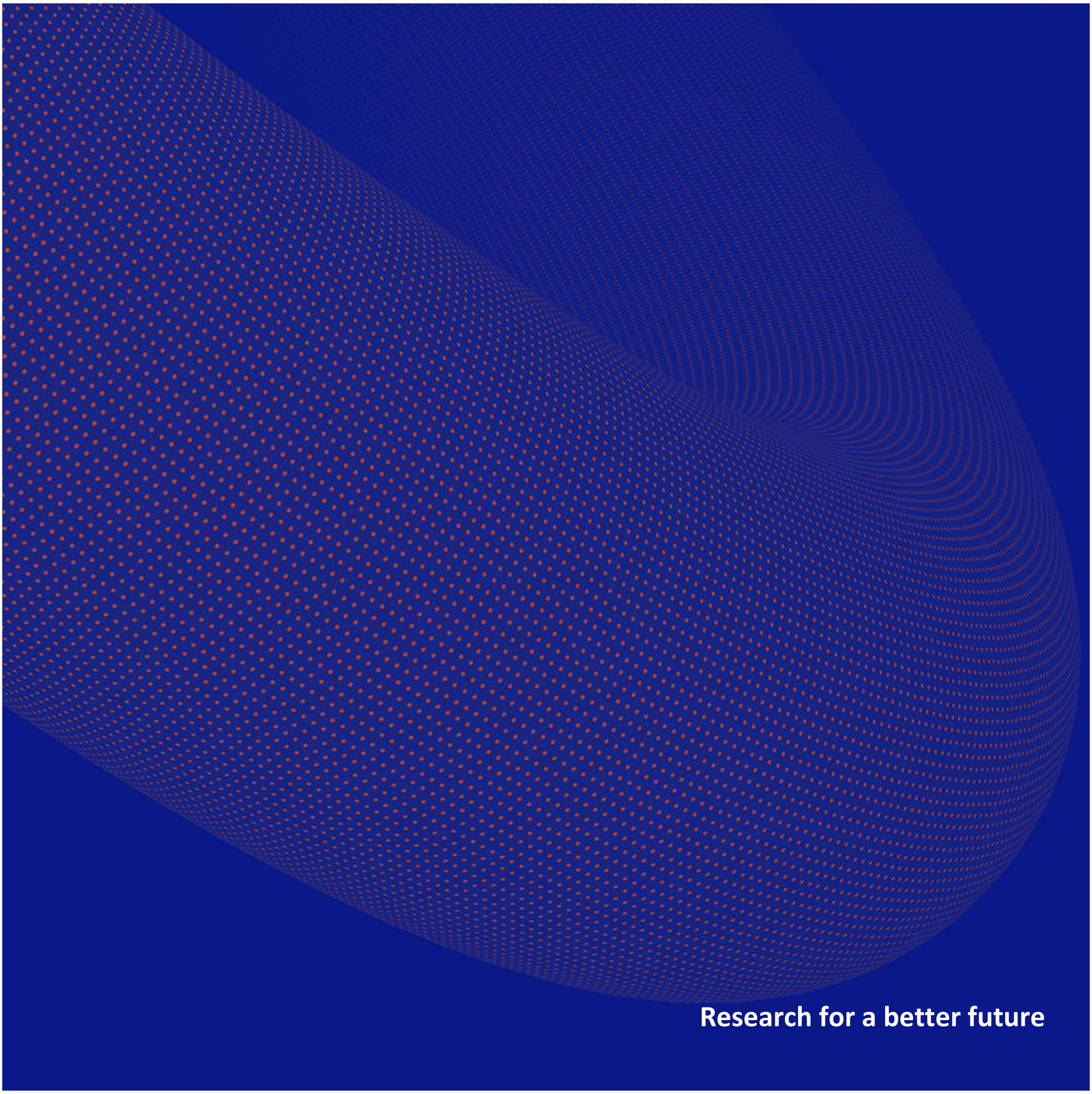

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Summary:

This report is developed as part of the research project *ZEVS: enabling Zero Emission passenger Vessel Services* and the aim of this report is to provide state of art overview and outlook of feasible bunkering options for zero emission high-speed vessels. The scope is limited to battery charging and hydrogen refueling, neither the safety aspects of the selected technologies are assessed.

The first chapters describe in more detail the service demands of high-speed vessels and the constraints in the grid.

It is common to charge existing battery electric vessels with a custom DC charger. Such a solution together with automatic connection and disconnection would also be feasible for high-speed vessels. Also, battery swapping could become an option where direct charging becomes challenging.

To offer hydrogen bunkering, hydrogen supply to the site should be assessed as it is still a novel energy carrier in the transport sector. Hydrogen bunkering as such can be done in different manners and very limited experience is present within the maritime sector. At the moment cascade filling seems to be the most suitable technology for high-speed vessels.

Developments in rules and regulations of hydrogen bunkering could decrease the legislative barriers. While standardization of charging solutions could decrease project costs and increase flexibility.

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Contents

1 Introduction

The research project *ZEVS: enabling Zero Emission passenger Vessel Services* funded by the Research Council of Norway (project No. 320659) aims to provide insights in how the Norwegian public transport with high-speed vessels can eliminate their emission. The work is multidimensional by developing knowledge about zero-emission high-speed vessels, how they can be charged/ refueled and how the operation as such can be optimized considering the public service it is offering. Work package three (WP3) of this project is looking into how the charging or refueling could be designed. This report aims to set the ground for WP3 by presenting state-of-the-art charging and refueling solutions for ships with a special focus on its feasibility for high-speed vessels. It will highlight the trade-offs which need to be considered and critical areas of further research. This work is limited to exploring the infrastructure solutions for the most common types of zero emission technologies for high-speed vessels, batteries and compressed hydrogen.

This report is led by IFE and written in cooperation with SEAM and Statkraft, who are participating industry partners in the ZEVS project. SEAM is a Norwegian leading supplier of hybrid and fully electric solutions to ships. Statkraft is a Norwegian hydropower producer that has become an international renewable power actor with a strong interest in developing a hydrogen supply chain. With their participation, this report gathers the latest state-of-the-art knowledge acquired by active commercial actors within the maritime charging and hydrogen refueling field.

Chapters 2 and 3 are describing high-speed vessels, including the challenges to provide a zero-emission service and the connected challenges to facilitate infrastructure in form of access to the grid. In chapters 4 and 5 the different possible ways to recharge batteries and refill compressed hydrogen are presented and discussed. In conclusions in chapter 6, the main trends and challenges within the field is summarized.

1 High-speed vessels

In this chapter, basic insights into high-speed vessels will be presented to give a better understanding of the type of vessels that will be served by the infrastructure.

In Norway different types of vessels are frequently used to transport goods, persons and cars to islands or along the geographically challenging Norwegian coastline. The distinction between what is a high-speed vessel and what is just a vessel can easily become ambiguous.

According to the Norwegian legislation (FOR-1998-01-05-6), a high-speed vessel should have a length of 24 m or more and be able to operate at 20 knots or more. The Norwegian legislation does not correspond precisely to the International Code of Safety for High-Speed Craft (HSC Code) provided by the International Maritime Organization (IMO). The intention of the HSC code is to provide rules and standards for vessels using non-conventional ship building materials such as aluminum or composite sandwich materials, which are essential for building high-speed vessels. However, to build according to the HSC code does not require any minimum speed of the vessel. On the other side, within the HSC code, a definition of HSC as a function of its speeds and volume of displacement is included. The shortcoming of this definition is to calculate the volume of displacement in a sensible way and combine it with the maximum speed for each unique vessel.

To increase the confusion further, the unique set of high-speed vessel routes provided by the different Norwegian regions, and which is entitled national economic support scheme, are not necessarily operated by a high-speed vessel according to any of the above-mentioned definitions. Therefore, extra caution should be made to define the set of high-speed vessels which are considered. If not specified otherwise, the work here refers to a high-speed vessel according to the definition of the HSC code.

As a public mean of transport for middle to long distances the speed of high-speed vessels becomes an important parameter. The trade-off to operating the vessel at higher speeds is the energy demand which increases exponentially with speed. To a certain extent, the energy penalty can be offset by building light-weight vessels with low water resistance.

These properties of high-speed vessels are also central when considering how they can be operated with zero-emission technology by storing energy in either battery or hydrogen. Especially considering the high sensitivity for weight and high energy demand relative to the vessels size when compared to other ship types such as battery-electric vessels for transporting cars and passenger.

The Norwegian high-speed vessels typically carry between 42 to 296 passengers and have a size between 30-40 m. The catamaran hull is the most common design, while single hull designs also exist [1]. There is an ongoing exploration of innovative hull designs to further improve the energy efficiency such as using hydrofoils or Surface Effect Ship (SES) design [2].

Figure 1 shows the representative energy consumption at the propeller shaft for a conventional hull as a function of the vessels speed for different vessel sizes. It highlights how sensitive the energy consumption is relative to the vessels speed, and that the increase becomes sharper for higher speeds. As an example, with an increase of speed from 20 to 30 knots, which is a 50% rise in the velocity, the energy consumption more than doubles.

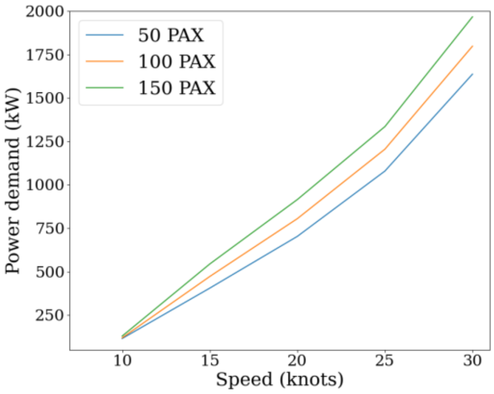


Figure 1 Example of energy consumption at propel for high-speed vessels [3]

Even if the power demand for a single high-speed vessel with a representative hull is known, there are surprisingly little data available on how the energy demand looks like for the current fleet of vessels and for different routes. Sundvor et.al. [1] studied the movement patterns for the Norwegian fleet of high-speed vessels with a simplified hull resistance model. The findings showed that the median daily energy demand per vessel is approx. 5 MWh at propeller shaft, while the median for different vessels can vary from <1 MWh up to 24 MWh with significant variation between days. It has shown to be difficult to verify these calculated values with real-world data.

The high-speed vessels can engage in several different operations. This can be serving one route once or several times per day, operating a combination of routes, be catered for tourist trips, or doing other trips. Therefore, it becomes difficult to disaggregate a vessels energy demand to energy demand for individual routes. Aarskog and Danebergs [4] estimated the energy demand on route level based on confirmed and estimated diesel consumption for scheduled high-speed vessel routes. The energy demand per a single completed route varies between 0,015 to 10 MWh with a median of 1,3 MWh.

As the median of the daily energy consumption of the most energy consuming high-speed vessel fits the roundtrip of the most energy demanding route, the data seems coherent on an overall level.

The routes of high-speed vessels can be two end-stops usually with stops along the trip or a loop where the start- and end-stop are the same. The stops along a route can either be fixed or be made upon request. They are typically not longer than 3 minutes. The heterogeneity of route types and utilization of vessels makes it challenging to identify representative decarbonization solutions across this transport segment.

A better understanding is needed of how different routes could be decarbonized (rather than individual vessels) and what requirements it would implicate for the infrastructure. This is work that needs to be further developed within the ZEVS project.

2 Power grid

Electrifying high-speed vessels will put additional strain on the power grid when the high-speed vessels need charging or refueling of green hydrogen. This transition can already be observed in the deployment of battery electric vessels for cars, where the grid capacity near the harbors is usually very limited and usage of onshore batteries are common. On the other hand, green hydrogen can be competitive with electric charging when produced regionally or locally, since the production of green hydrogen can be performed over a longer time period compared to the electric charging of the vessel, resulting in lower peak demand. However, for already constrained grids, local production of green hydrogen will give an additional strain on the grid [5].

Due to the grid's crucial role to facilitate the usage of zero-emission high-speed vessels, it is important to understand its main characteristics and limitations. The grid is typically divided into central, regional and distribution grids. Their differentiation is based on voltage levels, which together with the current are the main parameter to define available power from a power line.

It is challenging to understand how much power the grid can deliver at any given point along its system. As an upper limit of the power available is the technical capacity of what a single power line can deliver within its safety parameters. However, other components could limit the available power such as capacity in transformers, circuit breakers, or switchgears at relevant voltage levels or higher up in the system. The Distribution System Operators (DSOs) have a duty to offer network to those who want access. This is a part of the DSOs responsibility to connect and investigate available grid capacity for approaching customers. However, the DSOs are also required to operate their network under safe conditions meaning that the connection of new power demanding customers must not affect the security of supply for the other grid customers. This applies both under normal operating conditions and during outages in the system[1]. Even if we understand how much power the system could deliver at a specific location, the location for the new demand will be decided by the spare capacity when the existing demand at the location is considered. This illustrates the complexity related to estimating probable available spare capacity in the grid [6].

When a customer with an expected large consumption (consumption of more than 1 MW) wants to connect to the grid, the customer needs to apply for connection through the DSO, in some cases also the Transmission System Operator (TSO). All the applications for network connections end up in a queuing list with the DSO and TSO. The DSO then investigates if there is enough available capacity in the grid and operationally possible to connect the customer. If there is not enough spare capacity in the network, the DSO needs to investigate the related grid reinforcement cost, both in relation to upgrades on lines/cables and transformer/substation. Additionally, it is possible in some situations to connect a customer on specific terms. This means that if the capacity of the grid is exceeded in a time period, the DSO can disconnect customers that are connected on terms, and by that ensuring safe operation of the grid. When planning for the electrification of high-speed vessels, it is important to take into account the possible additional cost related to grid connection and grid reinforcements.

It is important to understand which voltage level could be suitable for a given power demand. To get a better insight, the capacities in the power lines are examined as follows. A dataset with information on the diameter of copper equivalent cables in the Norwegian regional grid was received from the Norwegian Water Resources and Energy Directorate (NVE from its Norwegian abbreviation) [7]. With help of this document, it was possible to correlate expected cable resistance from the copper equivalent cable diameter for the different voltage levels, which was matched with market type cables [8]. As a next step, guidelines from Statnett of maximum current for identified commercial cables was

[1] Generally, to satisfy security of supply enough redundancy in the regional and central grid it should withstand a failure in any single component of the system and still avoid any black-out. Also known as n-1 criteria.

used to assume max current in most demand conditions [9]. With known voltage and current, max available power was identified and is shown in Table 1. It should be noted that cable diameter can vary a lot within the same voltage level, so the estimates of power outtake at different voltages are a very general approximation. Considering the many location-specific constraints for the power outtake as mentioned previously, the most realistic available power will be a smaller fraction of the power available from the representative cable type for a given voltage level or no available capacity at all.

Table 1 A rough estimations of possible capacity for different voltage levels and available capacity in the distribution and regional power grid.

kV	Representative cable type	Current rating (A)	Capacity at various utilization rates (MW)		
			100%	50%	10%
24	80-AL1/13-ST1A	303	11,3	5,7	1,1
66	151-AL1/25-ST1A	506	52	26	5
132	402-AL1/52-ST1A	908	187	93	19
145	402-AL1/52-ST1A	908	205	103	21
300	806-AL1/102-ST1A	1394	652	326	65

3 Charging battery electric high-speed vessels

Design and technology for charging electric high-speed vessels are under constant development. The solutions have a lot in common with chargers for electric and hybrid vessels, which by now is a common sight in Norway. Due to variations in requirements for charging speed, size, automation and appearances, and lack of standardization, most shore chargers vary from site to site.

As mentioned in chapter 3, the electric grid plays a huge part in designing a shore charger. Due to the lack of infrastructure and electric grid power in many quays, energy storage, can be used to supply sufficient power over a short period of time.

3.1 Conductive charging

The conductive charger is the most used solution for charging electric vessels with charging plugs connecting to the vessel from shore. Today there are many different variations of how to connect these plugs to the vessel with both manual and automatic solutions.

As high-speed vessels have many short stops at the quays, the most sought-after solutions are charging towers with automatic connections and disconnections of charging plugs when entering/leaving the quay. The design and functions of these charging towers will vary from site to site and are dependent on the vessel design.

The vessel charging system can be designed for either receiving AC or DC power. AC power can be used either by commercial industrial type power sockets with limited charging power or custom-built maritime chargers for higher power outtakes. With an onboard battery, a rectifier would be needed onboard which adds weight. [10].

3.1.1 DC charging system

Charging systems onshore are designed with one or several main supplies from the shore grid, whereas each of them powers an independent drive charger switchboard. A transformer may be part of the system to assure correct voltage input for the active front end rectifier (AFE). An AFE will effectively work as an ACDC-converter taking the alternative current input from the grid and converting it to direct current suitable for charging maritime batteries. The Active Front End rectifier is used to minimize electrical disturbances on the grid when converting AC to DC.

If a battery system is included in the shore charger system, the battery has a dedicated battery management system (BMS) and its power flow is controlled by a DCDC-converter.

The charger switchboard has switchgear to connect to the onboard vessel battery systems through charging plugs. Control, alarm and monitoring are performed by a common control system. A Programmable Logic Controller (PLC) in the Shore Charger controls all functions within the charger. The PLC control hardwired IO, converter fieldbus interfaces and an interface to the BMS for battery safety in case such a system is part of the scope.

The Shore Charger must be capable of reducing power drawn from the electrical grid in case the charger ratings exceed the power available on the local grid, in case of temporary limitations imposed by the grid administrator, or in case several chargers need to share the available power. The system is also capable of providing reactive compensation by actively adjusting the power factor.

A typical and simplified Power Topology is provided in Figure 2 below to give an overview of the principal electrical system structure.

The vessel is charged with a variable DC voltage through plugs, and DC-contactors are available to connect and disconnect the vessel. Pilot pins are also used for interlock- and signal interface between the shore charger and vessel. The amount of voltage sent through the charging plugs to the vessel is determined by the batteries onboard. Normally the batteries can withstand 800VDC-1000VDC. Switch disconnectors are also part of the charging circuit to enable manual disconnection in case of maintenance and similar.

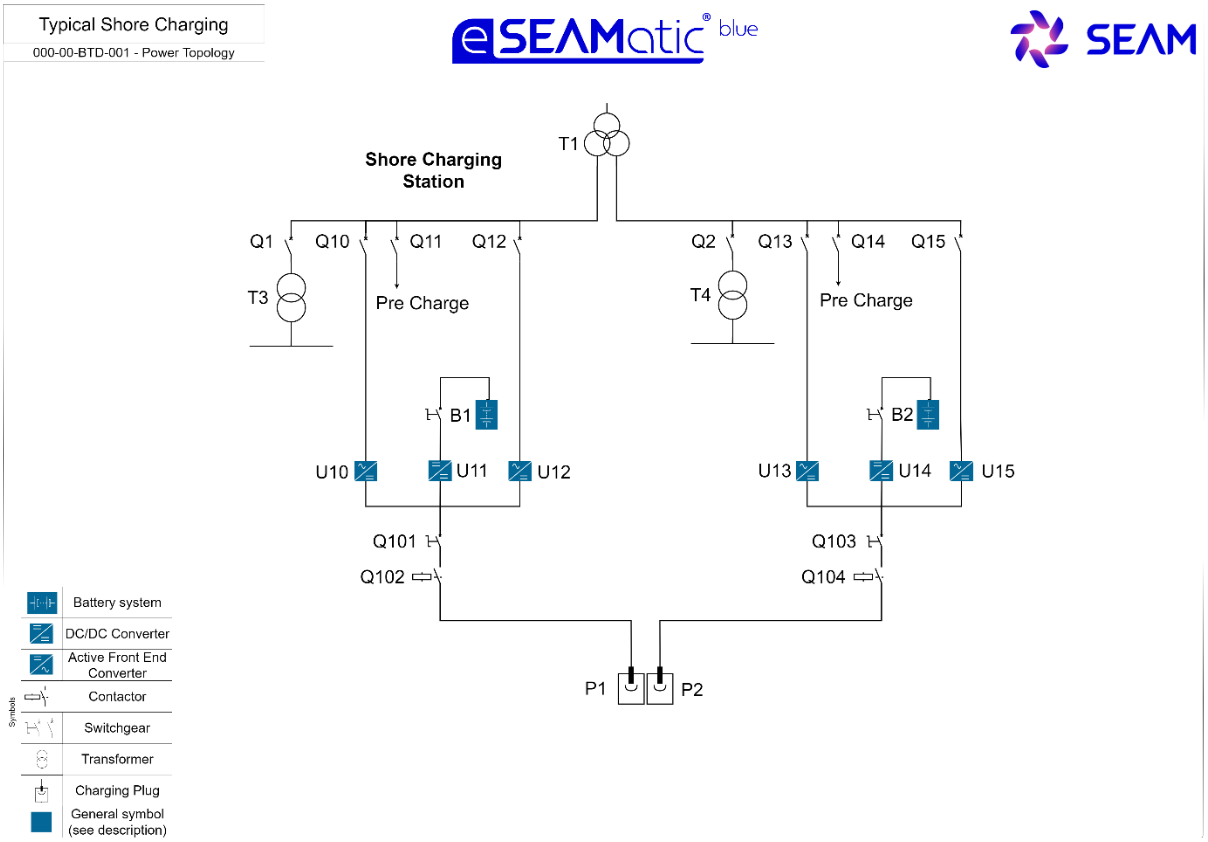


Figure 2 A typical simplified power topology of a shore charging system including batteries and two charging plugs from SEAM AS

The cost of charging systems on quays varies a lot due to the large difference in available grid power on the locations and necessary improvements on the infrastructure needed before installing technical buildings and charging towers. Table 2 presents an estimated cost from SEAM AS on charging systems of different sizes. The estimations do not include upgrades of the power grid and infrastructure changes on sites. Most charging systems are built differently depending on location and vessels that intend to use them.

There is also an added cost of installing a charging tower with compatible plugs. The cost of these charging towers varies a lot depending on the charging system design. Some towers can autonomously plug in and eject the charging plug, and some needs to be plugged in manually. Most common for high-speed vessels will be to use automated cable cranes that connect and disconnect using different sensors to detect positioning and connection/disconnection of plugs. In Table 3,some indicative costs for manually plugged charging towers are presented. Budget prices for automatic charging towers are harder to suggest as they vary a lot in price from quay to quay and vessels. Many factors for different infrastructure at shore and the amount of power needed to charge the vessels make it difficult to give a budget price for these systems. Operators also have many different needs and wishes for how the towers should be designed. Some examples of automatic charging towers are shown in Figures 3, 4 and 5.

Figure 3: Automatic charging tower from Zinus.

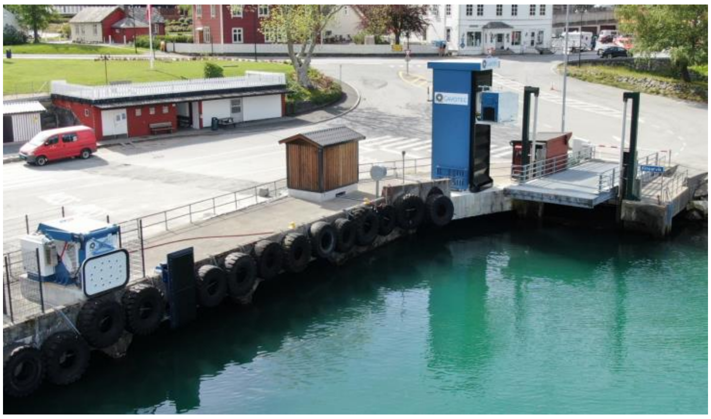


Figure 4: Automated charging tower and moormaster from Cavotech

Figure 5: Fully automatic pantograph delivered by SEAM

Table 2: Estimate of charging system cost for systems including and excluding onshore battery, from SEAM AS

Charging power	Cost (KNOK)	
	Without onshore battery	With 500 kWh onshore battery
500 kW	6 050	10 550
1000 kW	6 600	11 100
2000 kW	9 130	13 630
3000 kW	9 800	14 300
4000 kW	11 880	16 380
5000 kW	13 530	18 030
6000 kW	15 180	19 680

Table 3: Rough estimate of cost for a manual charging tower. For higher power output, more plugs are needed, from SEAM AS.

Power	Cost (KNOK)
Up to 2400 kW	1 650
Up to 3000 kW	2 200

There is yet to be decided on a standardized design for the plug and the automatic connection process. Currently, the functions and features of the plugs for charging and the cable dispenser, connecting the plug to the rest of the onshore charging system, vary a lot depending on the suppliers and projects. If a standard charging plug is decided upon it would benefit all vessels due to a higher availability for charging along the coast. Such standards could facilitate the electrification of the maritime sector beyond just charging vessels. Charging facilities would also have a longer lifespan due to not having to change any infrastructure if a new vessel operator takes over a route, making the electrification of the vessels more affordable. However, it is important to have a mature technology before standardization.

3.1.2 Location, housing and auxiliaries

These types of charging systems are normally installed in a building located on the vessel quay. Size, design, and functions vary from project to project, and are very dependent on location and landowners/operators wishes. Available space on quays can vary. In some cases, it is possible to fit standard systems delivered in 20ft container houses, or for them to be installed in existing building structures. However, this might require new infrastructure to be built to accommodate parts of the onshore charging system depending on available space and safety zones. Vessel quays are often located at remote sites where there are large unpopulated areas and making changes to infrastructures to fit new technical buildings or charging towers can be done from the technical point of view. However, this will require more investments, space and other considerations. In more dense areas it is often more costly to make necessary changes to infrastructure, and more innovative solutions are required. One example is a submerged floating structure with room inside for switchboards and transformers.

The room containing technical equipment on the quay is usually ventilated and cooled by a fan-coil unit and a heat exchanger to glycol circuits in seawater.

3.2 Inductive

Through inductive charging, a vessel can be charged and at the same time avoid mechanical contacts that can wear and tear in the corrosive coastal climate. In addition, the process of starting and stopping the charging event can be faster as the charging coil only need to approach the receiving coil at the vessel to start the charging. However, attention still needs to be made to ensure acceptable alignment between the onshore and the vessels charging points remains.

There has been a continuous development of high power indictive charging, with a large focus on road transport, as well as rail transport which has resulted in several pilot projects [11-13]. There has also been made dedicated efforts to study and apply inductive charging in the maritime sector [10, 14]. Today, there are two battery electric vessels operating with inductive charging. This is a small river crossing vessel in Fredrikstad charged with a 100 kW charger and the car vessel MF Folgefonn (pilot project) which is charged with a 1,2 MW charger [15]. In the latter case, the vessel is also held in place with a vacuum mooring system that permits up to a 50 cm gab between the charging and receiving coil [16].

Models of inductive charging show slightly lower efficiencies than charging performed with a DC plug [10], which speaks in favor of this technology. However, inductive charging requires a receiver coil on board the vessel which might impact the weight of the vessel negatively in comparison with other charging solutions.

3.3 Battery Swap

Automatic battery swap (ABS) can be another technical approach for energy transfer onboard. Such a solution can dramatically reduce the amount of time a vessel has to lay by the quay to get a fully charged battery. At the same time, the systems peak power can be significantly reduced as the empty swapped out battery can be charged over a much larger time window. A new and innovative automatic battery swap solution is being developed by SEAM AS and visualized in Figure 6.

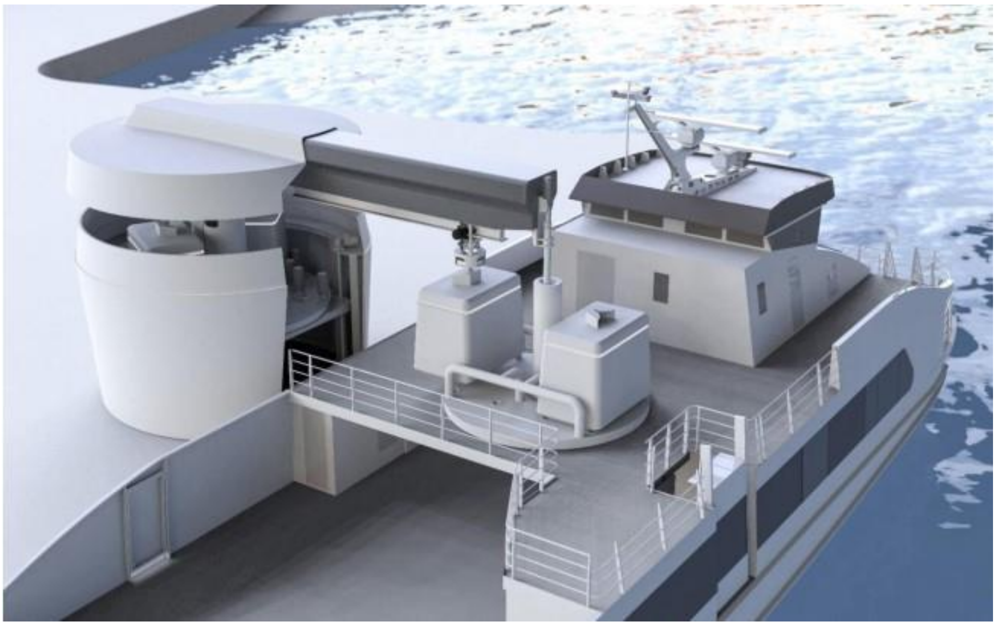


Figure 6: Example of concept drawing of battery swap solution developed by SEAM AS.

A battery swap solution will as mentioned greatly deduct time at the quay and make it more feasible for high-speed vessels to use batteries if the bottlenecks are charging time or power grid. Batteries are still a heavy solution for high-speed vessels but having a battery swap system located at the different quays can be a viable solution for routes where the distance between the stops are not too long.

The automatic crane shown in Figure 6 consists of a steel tower structure, a crane, and a belt within the tower structure to store and charge three battery containers. The crane can only serve one vessel at a time and should be capable of swapping two battery packs within three minutes. The ABS contains a rod at the end which will be lowered onto a cylinder cone at the vessel to connect the vessel before the operation begins.

The control system is split into separate parts on shore and on the vessel, communicating with a dedicated radio link. The core of the shore control system will be a PLC that controls all the functionality. It will monitor and control vessel identification and positioning including Battery Transfer Robot (BTR) position and movement. An operator panel on shore is available for operator monitoring and manual control of the BTR. The PLC will handle all communication with the battery carrousel at the vessel which has a separate control system.

4 Refueling fuel cell electric high-speed vessels

In contrast to the well-developed power grid, hydrogen production and usage have until now mainly been concentrated in a few industrial applications. To offer a hydrogen refueling solution for the transport sector it is crucial to consider efficient production and, if required, also transportation of hydrogen. The value chain for using hydrogen in the transport sector is currently under development and the Norwegian state is supporting the building of five hydrogen production facilities along the coast with approx. 700 million Norwegian kroner [17].

Thereby a broader approach is taken in this chapter to explain the most relevant parts for producing and delivering hydrogen for future hydrogen high-speed vessels.

4.1 Hydrogen production and distribution

This section will first introduce and described hydrogen production with electrolyzers including a differentiation among different types of electrolyzers. As it is not always convenient to have production at the same location as the refueling station, options for hydrogen distribution will also be described.

4.1.1 Production

With the aim of creating zero emission solutions and not only moving the location of emissions, the consideration of low emission production of hydrogen is essential. The European Union has stated that hydrogen produced with emissions below 36.4g CO2eq/MJ H2 (4.37 tCO2/tH2) is classified as low-carbon, either it is from the power grid or from natural gas where carbon emissions as captured and stored (also known as blue hydrogen) [18].

In this report, we will focus on hydrogen production with electrolyzers connected to the electrical grid. When developing a hydrogen value chain, the first element of strategic choice is related to the production site; centralized or de-centralized. This selection will determine the scale of production, concept, technology flexibility, and profitability of the value chain. To determine which concept, a sensitivity study of the Levelized Cost of Hydrogen (LCOH) should be performed.

Hydrogen production by use of electrolysis utilizes electricity to split water into hydrogen and oxygen gas. Currently, three types of electrolyzers are available, i.e. alkaline electrolysis (ALK), proton electrolyte membranes (PEM) and solid oxide electrolyzers (SOEL). The first two are illustrated in Figure 7.

Table 4: Investment costs in electrolyzers [19, 20]

	2,5 MW [USD/kW]	10 MW [USD/kW]	40MW [USD/kW]
PEM	2500	1233	839
ALK	2020	1000	676
SOEL	Not commercial available		

It can be assumed that roughly 50% of the electrolyzer installed power capacity can be translated into ton hydrogen pr day. For example, 10 MW will produce 5 ton/day hydrogen (compressed to 350 bar).

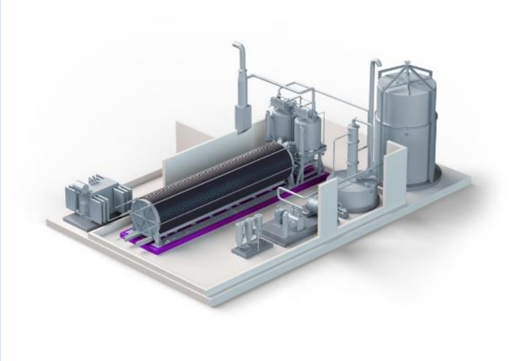
2.2 MW ALK System	1.25 MW PEM System
	

Figure 7 Illustrations of electrolyzers from NEL [21]

Alkaline electrolyzers represent a mature technology that has been utilized for more than a hundred years. The electrolyzers operate at 60-90˚C and use an aqueous KOH solution as an electrolyte. Examples of suppliers are NEL, HydrogenPro, Siemens, Green Hydrogen Systems etc.

PEM electrolyzers were introduced in the 1960s utilizing a solid, proton conducting membrane operating at 50-80˚C. Examples of suppliers are NEL, Cummins, ITM, Hydrogenics, Plug Power etc.

SOEL utilizes a solid, ceramic membrane to produce hydrogen and has been developed since early 2000. The operating temperature is 500-850˚C. Examples of suppliers are Haldor Topsøe, Sunfire etc.

Table 5: Electrolyzer technology summary [22, 23]

	System Efficiency [%]	LCOH [€/kg] *	Lifetime [h]	Response time to nominal capacity
PEM	54-61 %	~2.3	75,000	1s
ALK	62-73 %	~3.0	90,000	10s
SOEL	73-82 %	~4.4	20,000	1s (warm system)

* Over a period of 20 years with 2,000 hours of operation annually, an electricity price of 15 €/MWh (as seen with electricity from solar PV in South Spain), 3% O&M costs
DNV ETO 2022 Hydrogen Report.

The electrolyzer system will require additional equipment and consumables to produce hydrogen. This includes but is not limited to:

- Gas management system
- MV transformer/power distribution/rectifier
- Fresh water management system and purification
- Compressors
- Gas dryer
- Gas storage system
- Gas dispensing system (optional)

4.1.2 Distribution and storage

A major element defining the opportunities for hydrogen is how to efficiently distribute the produced gas to the consumer. The preferred alternative will depend on the location of production, volume produced, and bunkering solution. Currently, the most mature market is delivery of compressed hydrogen on trucks, certified according to the “European Agreement concerning the International Carriage of Dangerous Goods by Road” (usually abbreviated to ADR). The road freight is typically made by 20 or 40 feet containers and examples of such solution are shown in Figure 8. Their shortcoming is limited carrying capacity and high transport costs, especially for longer distances.

For a centrally sited electrolyzer system, pipelines have over decades been demonstrated to be a good alternative for large-scale hydrogen transportation. Only large industrial demands have until now been able to satisfy the necessary volumes to make pipelines a feasible option.

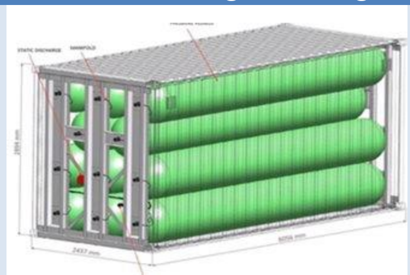
	Horizontal Fibreglass Storage	**Vertical Carbon Fibre Storage**
		
Cylinders	11	54
Hydrogen Mass	435 kg	487 kg
Operatingpressure (@15 °C)	350 barg	381 barg
Material	Fibreglass composite	Carbon and composite
Container weight	(~16,4 ton)	9,4 ton

Figure 8 Storage Containers for compressed hydrogen [24, 25]

Novel solutions are explored to fill the gap in affordable, flexible, and efficient hydrogen transport, such as sea transport of compressed hydrogen or by retrofitting existing natural gas pipelines. To deploy new ways of transport, innovation and development are needed both in the technical as well as in the regulatory domain, with a special focus on safety.

Table 6: Key summary of Distribution alternatives, Interreg/ ITM Power

	Truck	Pipe	Ship
Volumes [ton/day]	2 ton/day	2000 ton/day	68 ton /day
Distances [km]	< 50 -100	< 300	> 500
Delivery Pressure [bar]	350	70- 100	250
LCOT* [€/kg]	0,4 - 0,6	0,2	0,3-0,6

* LCOT = Levelized cost of transport

Concerning ship transport with compressed hydrogen, the Norwegian company Gen2 Energy targets to develop, build, own and operate an integrated value chain for green hydrogen within 2023. In recent development, Gen2 Energy is developing a series of newbuilt vessels for a seaborne logistics chain for green hydrogen [26].

As part of the Japanese-Australian Hydrogen Energy Supply Chain pilot project, the Kawasaki Heavy Industries (KHI) built liquefied hydrogen (LH2) carrier Suiso Frontier are sailing with LH2 from Australia to Japan. The vessel has 1,250-cubic-metre, vacuum-insulated double-shell-structure stainless steel LH2 cargo tank and is operated by Shell. The vessel is fuel by diesel. 22nd of April 2022 Kawasaki obtained Approval in principle (AIP) for 160.000 m3 LH2 carrier.

4.2 Hydrogen bunkering

In this section the bunkering itself will be discussed both by a general introduction and a more in detail explanation of three bunkering methods: pressure balance bunkering, pressurized bunkering, and tank swapping. In the end, the section will be wrapped up with a brief comparison of these methods.

Hydrogen refueling has become a much more mature technology serving the road transport, where the cascade refueling method is common. A safe standardized refueling protocol (SAE International J2601) is established as well as years of expertise have been gathered to optimize this technology.

The significant difference between the road and maritime applications is in the volumes of hydrogen needed. A passenger car will refuel around 5 to 7 kg of hydrogen, while a bus or truck will refuel tenths of kilograms of hydrogen. While a maritime application will require refueling in the scale of hundreds of kilograms of hydrogen. It means that the maritime refueling system needs to be dimensioned for demands approx. ten times higher than in the heavy-duty road transport. Even if the basic principle remains the same for cascade filling, there is no readily commercialized system that is compatible to refuel the demands required for a maritime application.

Bunkering of both liquid and gaseous ship fuels are common operation today, regulated by international and national authorities. Additional interest organizations such as Oil Companies International Marine Forum (OCIMF) also pursue standardization of and promoting best practices in the design and operation of ship bunkering solutions [27]. There is currently no specific regulation on bunkering of compressed and liquid hydrogen. Today, entities operating in Norway must obtain consent from The Norwegian Directorate for Civil Protection (or DSB from the Norwegian abbreviation) for bunkering of hydrogen. In addition, all part of the hydrogen system on board a vessel, from the bunkering flange, must be approved by the Norwegian Maritime Authority (NMA) and the vessels classification society.

There can be several challenges related to onsite hydrogen bunkering. Examples of challenges are safety zone for bunkering and production, noise, and other area demanding problems.
These issues could also lead to a challenging process with the regulation of the area, and this will lead to a more time-consuming process compared to a battery electric solution.

4.2.1 Pressure balance bunkering

The pressure balance bunkering is based on the principle that when two containers with gas at different pressure is connected, the pressure between the tanks will strive to equalize by mass (and thus pressure) flow from high pressure to low pressure tank.

Single Storage tank refueling

The simplest tank-to-tank refueling design provides only one stationary hydrogen storage tank at the port. The hydrogen vehicle connects to the station through a dispenser nozzle. Then the station opens for the storage tank, and a mass flow of hydrogen is forced from the storage tank to the vehicle tank due to the pressure difference. One disadvantage is the loss of compressor work as all gas needs to be compressed to a significant overpressure relative to the targeted equalizing pressure. This solution also increases the tank size and locks in a large volume of hydrogen in the onshore storage tank to only provide a sufficient volume of gas for the refueling event.

Cascade bunkering

In cascade refueling, hydrogen is filled from land-based tanks storing hydrogen at different pressure levels. The cascade tank storage system consists of tanks of different pressures, for instance, a high, medium, and low-pressure tank. When the vessel connects to the tank, the refueling starts from the low-pressure tank, proceeds to the medium tank, and finally the high-pressure tank until the ship onboard tank reaches max pressure (and mass). The rest of the process design is similar to the single-tank storage design mentioned above. In this design, the compressor work is decreased. In addition, a larger share of hydrogen stored on land can be transferred to the ship as part of the onshore storage will have an equalization pressure well below the target pressure of the onboard tank. An illustration of a cascade filling concept is shown in Figure 9.

For cascade refueling we have assumed the following system setup:

- Fixed storage tank filled by pipe from electrolyzer/compressor (380 bar)
- Bunkering unit, connections, dispenser with 2 parallel lines/nozzles for speed and redundancy
- Assumed pressure on vessel storage tanks 250 bar
- Filling rate 700-1000 kg/hour

The filling rate can be further increased by either adding flow to a single fueling line or adding more fueling lines in parallel. Both solutions drive complexity and costs.

While increasing the flow in a single line can seem like the simplest solution, the following two factors are impeding a simple implementation: i) an increased flow might require larger dimensions of the piping and refueling line to maintain acceptable pressure drops. A combination of larger flows and pipe dimensions increases the safety risks of failure and by that complicates the risk analysis of the system. ii) hydrogen is one of the few gases that increase in temperature when expanding. As the onboard storage tanks are sensitive to extreme temperatures, the present refueling standard for road transport is included an operating temperature range between -40 to 85°C. The combination of these factors requires active hydrogen cooling for safe refueling when surpassing certain refueling flows. The threshold flow can, however, vary where tank dimensions, how many tanks are filled simultaneously, and the pressure difference between onshore and vessel tanks are important parameters.

Statkraft considers cascade filling potentially attractive if the electrolyzer is located at the same site as the filling infrastructure. However, only a few sites will allow this, which makes it more restrictive in terms of rolling out a national refueling infrastructure.

The main technical barrier of cascade filling is the required storage volume needed to bunker a ship, which is closer to 1:2. Meaning you will need 2 ton of storage to bunker 1 ton to the ship. This is due to the tank heel (gas remaining in the storage tank). The physical and realistic limit for land storage is governed by regulative requirements for the storage of large hydrogen quantities (above 5 ton, DSB). Secondary barrier is the interface to ship, which will require high pressure hoses with large bore diameter or many hoses connected to the same manifold, which again challenge the regulative and working procedures. The main commercial barrier is the estimated cost, which probably is higher than other alternative bunkering solution. Hence the bunkering capacity will be a decisive factor to choose the bunkering solution.

Figure 9 Cascade filling from HYON [28]

4.2.2 Pressurized bunkering

By use of pressurized refueling, hydrogen is stored at low pressures and a booster compressor is used to increase pressure during bunkering of hydrogen into the ship. Since the hydrogen gas is compressed to the actual pressure in the vessel tank, no compressor work will be wasted, and onshore storage tanks can be kept to a minimum. The challenge with pressurized refueling is that large compressors are required to complete the refueling in the time frame required.

The vessel might be refueled by utilizing the tube trailer as a local storage that compresses hydrogen directly into the vessel.

- The trailers come to the port and connect to the tube trailer connection point and remain connected as local storage
- When refueling is required, high-capacity compressors transfer hydrogen from the compressor directly into the vessel. Three compressors will be used, with 2 being required to meet normal operation and 1 being redundant. Even if two compressors fail, the vessel will still be able to refuel.
- Hydrogen is dispensed via a high flow nozzle supported on an arm over the vessel
- Assumed pressure on vessel storage tanks is 250 bar

4.2.3 Fuel Tank Swapping

This option has a self-explanatory title of switching the entire empty onboard storage tank with a full one. This can however be done in several different ways depending on ship design, port infrastructure, and required bunkering time. A first overall classification is between Lift on – Lift Off (LoLo) and Roll-on Roll-Off (RoRo) storage solutions. Within each category, several sub-sets of loading are available vessels.

Previous studies based on short-sea shipping and coasters (ZeroCoaster 2021) bunkering operations with standardized 20" containers are techno-economical viable which also share synergies to be used in other industries to enable a functional logistic system at a low cost. The containers are available today certified for ADR but will require further marinization to comply with seaborn regulations such as The International Maritime Dangerous Goods Code by IMO (IMDG), Norwegian Maritime Authority and Ship classification societies.

There are already established regulations and procedures to handle dangerous goods in containers onboard as well as its handling in ports, which can facilitate the approval process of tank swapping. In addition, a simple, efficient, and safe design for frequently coupling and de-coupling of the entire storage tank(s) would need to be developed and approved. Such coupling would be designed for significantly lower hydrogen flows in comparison with the demand for high flow coupling to fill fast an empty onboard tank from shore.

Swapping hydrogen tanks on a high-speed vessel would require an onshore lifting system, as such equipment cannot be fitted onboard a high-speed vessel. It could be a standardized equipment such as a port crane or a reach stacker. An alternative would be a specially designed tank handling system similar to the battery swap system described in chapter 3.3 Battery Swap.

A swappable fuel tank that also probably is compatible with road transport, must be a sturdy standalone unit in comparison with fixed tanks integrated into the ship. As the tank itself stands to a large degree of the total storage weight (>90%), the weight increase of a sturdy swappable tank must be considered when evaluating this refueling option.

This technology is in the stage of development, for example in the ongoing research project GreenBulk with the aim to develop a bulk ship powered by compressed hydrogen [29].

4.2.4 Overview of refueling alternatives.

Even if there has been ongoing research on refueling passenger cars for several decades, the requirements and possibilities for maritime applications are drastically different. It makes it a poorly explored field with limited experience. Several research projects and commercial actors are exploring this field as this report is written.

The final decision on the most suitable refueling solution is an integrated decision where many different aspects need to be assessed. An overview of some of these aspects for all the described technologies is shown in Table 7. While Statkrafts techno-economic general comparison of two of the relevant technologies is presented in Table 8.

Table 7: Key Summary of bunkering alternatives for high-speed vessels according to Statkraft

	Port Cost	Ship Cost	Bunkering Time	Safety
Pressure Balance				
• **Single Storage**	High	Low	High*	Medium
• **Cascade**	High	Low – Medium	Medium – Low	Medium
Pressurized				
• **Pressurized**	High	Low - Medium	Medium - High	Medium
Hydrogen tank Swapping	Low	Unknown	Low	Medium
Battery swapping				
• **Lo/Lo with onshore handling equipment**	Low	Low	Low**	Low

* A high bunkering time with compressed hydrogen is estimated to 0.2 -0.4 ton/hr.
** A Low bunkering time with compressed hydrogen is estimated to 4 ton/hr

Table 8: Key summary of fueling alternatives according to Statkraft

	Pressure balance bunkering	Fuel tank swapping
Type	Cascade	Lo/lo
Bunkering pressure [bar]	250	350
Bunkering volumes [ton]	0.2 - 3	5-15
Bunkering speed [ton/hr]	0.5-2	3-4
LCOB[2] [€/kg]	High	Low

4.3 Rules & Regulations

As hydrogen refueling for maritime vessels is still a relatively unexplored field this chapter describes the main rules and regulations that are relevant in a Norwegian setting.

[2] LCOB, levelized cost of bunkering compressed hydrogen volumes in the range of 1 to 2.5 ton pr bunker operation

Bunkering of hydrogen and other flammable gases in Norway is covered by the Regulations of 8 June 2009 relating to the handling of flammable, reactive, and pressurized substances including requisite equipment and installations (FOR-2009-06- 602). However, more specific provisions are needed on how to deal with the bunkering of hydrogen, and the first version is currently under development by The Norwegian Directorate for Civil Protection (or DSB from the Norwegian abbreviation). Today, entities must obtain consent from DSB for bunkering of flammable gases before any bunkering operation is allowed. (MarHySafe, 2021).

For use of transport containers with hydrogen as fuel storage on ships, there are several rules and laws that may be relevant, some of the most important are mentioned below, administrative authorities are also stated:

- Road transport of hydrogen containers from hydrogen production to the quay (ADR Directive - DSB)
- Hydrogen storage on the quay (Major Accident Regulations, Regulations on handling hazardous substances, Internal Control Regulations, and ATEX directives - DSB and the Norwegian Labor Inspection Authority)
- Bunkering of hydrogen from quay to ship (Regulations as on quay, guidance specific - DSB) Use of hydrogen on ships (IGF regulations - primarily the Norwegian Maritime Directorate with the involvement of recognized class companies)
- Rules for the use of portable pressure equipment for stationary applications (TPED / PED - DSB)

As for now, each project has to conduct an alternative design process according to IMO MSC. 1/Circ 1455. The equivalence of the alternative design shall be demonstrated as specified in the SOLAS regulation. An overview of applicable codes and functions can be derived from the ZeroCoaster project [30] and is shown in Table 9. The national rules are administrated by DSB and the Norwegian Maritime Directorate (NMA) [31, 32].

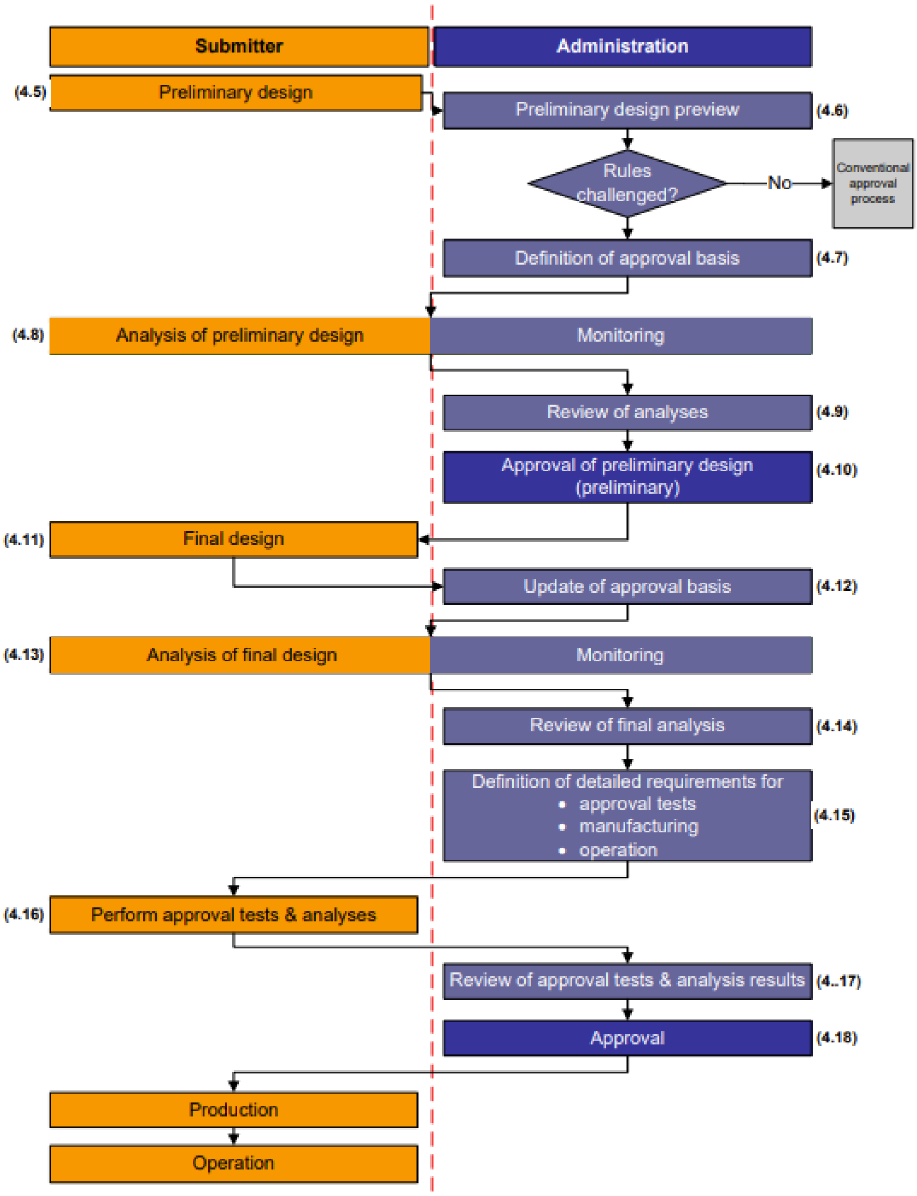
Dimensioning regulative requirements are normally not derived from deterministic design requirements but are calculated based on equivalent safety through a process called Quantitative Risk analysis (QRA). The QRA is the final conclusion to determine the safety distances, hazardous zones, and whether the safety precautions and procedures are meeting the equivalent safety as for other low flash-point gases specified in the IMO IGC.

Table 9: List of applicable rules

INTERNATIONAL RULES	International Convention for the Safety of Life at Sea 1974, with amendments
	International Convention for the Prevention of Pollution from Ships
	Interim recommendations for carriage of liquified hydrogen in bulk IMO MSC.420(97)
	International Maritime Dangerous Goods (IMDG) Code
	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels IGF Code
	Guidelines For The Approval Of Alternatives And Equivalents As Provided For In Various Imo Instruments MSC.1/Circ.1455
	MSC-MEPC.2/Circ.12/Rev.2 IMO revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process
	Handbook for Hydrogen-Fuelled vessels – MarHySafe JDP Phase 1 – 1st edition (2021-06)
NATIONAL	FOR-2014-07-01-1072 Forskrift om bygging av skip
	FOR-2014-07-01-1099 Forskrift om brannsikring på skip
	FOR-2001-12-04-1450 Forskrift om maritime elektriske anlegg
	RSR 18 – 2016 Regulations on ships using fuel with a flashpoint of less than 60°C
	RSV 12-2016 Veiledning om kjemiske lager for energi maritime batterisystemer

CLASS RULES	Pt.4 Ch.1 to Ch.6 Machinery and piping
	Pt.4 Ch.7 Pressure equipment
	Pt.4 Ch.8 and Ch.9 Electro and control systems
	Pt.4 Ch.10 Steering gear
	Pt.5 Ch.8 Compressed natural gas
	Pt.6 Ch.2 Propulsion, power generation and aux. systems
	Pt.6 Ch.2 Sect.1 Electrical energy storage
	Pt.6 Ch.2 Sect.3 Fuel cell installations – FC
	Pt.6 Ch.2 Sect.5 Gas fuelled ship installations Gas fuelled LNG
	Pt.6 Ch.2 Sect.6 Low flashpoint liquid fueled engines LFL fueled
	Pt.6 Ch.2 Sect.14 Gas Fueled Ammonia

Figure 10 Process diagram – Alternative design NMA/ RSV 12-2020.



4.4 Examples of projects

There are several projects opting for the use of compressed hydrogen as a fuel. In Norway, the first hydrogen vessel will utilize liquid hydrogen, which is named MF Hydra. Since then, the competence and incentives from authorities in the market have multiplied and derived into new studies and projects.

The development of most of the Norwegian projects has been supported economically by governmental research and commercialization funds. As mentioned at the beginning of the chapter, infrastructure is also supported by the same funds and coordinated to suit the operation of many of these vessels.

An overview of some relevant projects at the operation, building, and planning stages and what type of bunkering solution they are considering is listed in Table 10.

Table 10: Public known projects in Norway using hydrogen and internationally using compressed hydrogen

Ships/project name	Ship Type	Storage type	Bunkering type	Delivery & Status	Location	Ref.
SeaChange	Vessel	CH_2	Cascade	2022	USA	[33]
MF Hydra	Ro Pax	LH_2	Liquid	2022	Norway	[34]
Hydrotug	Tug	CH_2	Cascade	2023	Netherland	[35]
GreenBulk	Bulk ship	CH_2	Swapping	2024	Norway	[29]
Topeka	Ro/Ro bulk	LH_2 or CH_2	TBC	2024	Norway	[36]
FPS Maas, Rijn & Waal	IWW Barge	CH_2	Cascade	2024	Netherland	[37]
Vestfjord	Ro Pax	CH_2	TBC	2025	Norway	[38]
Samskip	Container	CH_2	TBC	2025	Norway	[39]
ThorDahl	Bulk	CH_2	Swapping	2025	Norway	[40]
Fremtidens hurtigbåt	High-speed Vessel	CH_2	Cascade	2025	Norway	[41]
HySeas	Ro Pax	CH_2	Cascade	TBC	Scotland	[42]
Scripps IO	Research	CH_2 & Diesel	Cascade	TBC	USA	[43]
NYK	Vessel	CH_2	Cascade	TBC	Japan	[44]

5 Conclusions

This report has presented the most important aspects of providing infrastructure to zero emission high-speed vessels, which can be expected to have a daily energy demand at propeller shaft from less than 1 MWh per day to more than 20 MWh. In extreme cases, the energy demand can be much higher. The work has been limited to only evaluate the infrastructure of charging batteries and refueling compressed hydrogen.

The maritime charging systems have been evolving for the last years as they have been installed for Norwegian electric and hybrid car vessels. A common and suitable solution for high-speed vessels is DC charging with a charging tower that autonomously connects and disconnects when the vessel is entering and leaving the quay.

As battery size onboard is a stringent limitation for high-speed vessels and as their stops except for end stations are very short, they would require high power chargers along their route. This becomes an important constraint for longer routes as the strengthening of the grid brings time and cost uncertainties. One possible option to efficiently offset the challenges would be battery swapping.

The bunkering of hydrogen for maritime vessels is currently in a very early phase. Due to lacking infrastructure, a broader approach is necessary to build up both production and bunkering of it. Transport of hydrogen might also be necessary.

There are several manners to bunker hydrogen, but both from technical assessment and project pipeline cascade refueling system and tank swapping crystallize as feasible alternatives.

Tank swapping is a flexible option where many steps of this method are already explored in a maritime setting. On the downside, as it is a novel refueling solution compared to a broadly deployed cascade system in the road segment, it might face unforeseen technical or regulatory challenges. The increased weight of a swappable tank also plays in its disfavor.

A cascade system could be a suitable solution for high-speed vessels as it is a well explored and efficient method for refueling. It is however facing uncertainties about how to scale the system up in a safe and efficient manner from road to maritime transport.

Installations to serve both battery and fuel cell vessels needs to be robust by following set rules and regulations. Even if this area is much more known for battery charging than hydrogen refueling, it still lacks a standardized charging interface. As a result, project costs are increased and limit the flexibility of the existing battery electric car vessel fleet and coming high-speed vessel fleet.

The limited experiences of hydrogen bunkering expose fuel cell high-speed vessels for barriers regarding approval processes as no safety standards specific for hydrogen bunkering are present in Norway.

Many fuel cell powered vessels that use compressed hydrogen are in the developing phase or under construction together with infrastructure serving them. Only refueling with cascade and tank swapping solutions are considered, even if many variations within these bunkering types might be applied. Rapid technology development and decreased regulatory barriers can be expected as experience accumulates from these projects and by that closing the experience gap relative to charging.

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